Assessing alternate furrow strategies for potato at the Cherfech irrigation district of Tunisia

by

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Abstract

Irrigated agriculture faces intense competition for water in Mediterranean environments. In this paper, alternate furrow irrigation was explored for a potato crop in the conditions of the Cherfech irrigation district, located in the Medjerda project of northern Tunisia. A field experiment was performed involving seven furrow irrigations in three irrigation treatments: alternate furrow irrigation (AFI), fixed furrow irrigation (FFI), and continuous furrow irrigation (CFI). Crop yield and water productivity were determined in all treatments. The experiment involved detailed irrigation evaluation and soil water measurements in the first three irrigation events. Soil infiltration (estimated with a surface irrigation model) was larger for CFI than for AFI or FFI. This finding was confirmed by the average irrigation depths,

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which amounted to 65, 60 and 91 mm for the AFI, FFI and CFI treatments, respectively. Application and irrigation efficiency were higher in FFI than in AFI, while in CFI efficiency was much lower. Water productivity (expressed as the ratio of yield to irrigation water) amounted to 8.0, 8.7 and 5.9 kg m^{-3} for the AFI, FFI and CFI treatments, respectively. Soil water–yield simulations indicated that alternate furrow irrigation did not result in reduced yield, neither for the experimental treatment nor for deficit irrigation scenarios characterised by six or five irrigation events. Alternate furrow irrigation stands as a simple management technique resulting in relevant water conservation in the local conditions.

Keywords: alternate furrow; potato; infiltration; levelling; on-farm; evaluation; models

Nomenclature

a	Kostiakov infiltration exponent, dimensionless;
AFI	Alternate furrow irrigation;
ANOVA	Analysis of variance;
b	Parameter of a modified Kostiakov infiltration equation (mm h^{-1}) representing the long-term infiltration rate;
c	Parameter of a modified Kostiakov infiltration equation (mm) representing instantaneous infiltration;
CFI	Conventional furrow irrigation;
DAP	Days after planting;
DU_{lq}	Distribution uniformity of the low quarter, dimensionless;
Ea	Application efficiency, dimensionless;
Es	Water storage efficiency, dimensionless;
ET_0	Reference evapotranspiration, mm;
ET_c	Crop evapotranspiration, mm;
FFI	Fixed furrow irrigation;
IE	Irrigation efficiency, %;
k	Kostiakov infiltration parameter, mm h^{-a};

Kc Crop coefficient, dimensionless;

Ky Coefficient relating standardised evapotranspiration and yield, dimensionless;

n Manning roughness coefficient, dimensionless;

p Soil water depletion factor for no stress, dimensionless;

P Precipitation, mm;

$RMSEs$ Root Mean Square Error in soil water storage, mm;

TAW Total available water, mm;

T_{max} Average maximum temperature, °C;

T_{min} Average minimum temperature, °C;

WP_2 Water productivity based on the irrigation water diversion, kg m^{-3};

WP_4 Water productivity based on the water beneficially used, kg m^{-3};

Z infiltration, mm;

Z_r Target irrigation depth, mm; and

τ Opportunity time, h.

Introduction

In the last decades, water resource managers have faced difficulties to satisfy the multiple, ever-growing water demands of semi-arid areas. This is particularly true in the Mediterranean basin, where an increase in irrigation acreage and intensity has been accompanied by a decrease in available water resources due to demographic growth and to concurrence with development-related activities (Abu-Zeid and Hamdy, 2002). In order to sustain agricultural production, a more rational agricultural water use is required; particularly in areas where the current irrigation systems and practices are largely inefficient. This is the case of many traditional surface irrigated areas in the Mediterranean basin. When addressing this problem, Allan (1999) identified three solutions: 1) using virtual water; 2) increasing economic efficiency; and 3) increasing the technical efficiency. While the third solution is the least adequate from the economic standpoint, it represents a common choice for water planners (Playán and Mateos, 2006). This solution often requires very relevant private and public investments, and frequently yields moderate results.

Surface irrigation has seen a significant decrease in Mediterranean environments. Farmers have installed pressurised irrigation systems to reduce water and labour input, following global trends. In California, Orang et al. (2008) presented a survey of irrigation systems that reported a decrease in surface irrigation acreage from 80% in 1970 to 50 % in 2001. In Spain, an intense period of irrigation modernisation at the beginning of the 21st century has reduced the extent of surface irrigation to 37% of the irrigated land (Government of Spain, 2006). In Tunisia, it is estimated that 54% of the irrigated area currently uses different types of surface irrigation, mainly furrows and micro basins (AQUASTAT, 2005). Surface irrigation will remain a relevant irrigation system in Mediterranean areas in the next decades. Surface irrigation performance has often been more associated with irrigation management than structural issues (Clemmens and Dedrick, 1994). Addressing irrigation management constitutes an attractive way to alleviate water scarcity in the Mediterranean basin, since this strategy requires no new infrastructure. Surface irrigation performance is affected by aspects such as high infiltration rate, soil heterogeneity, the quality of land levelling and inadequate irrigation discharge (Clemmens and Dedrick, 1994; Zapata et al., 2000; Playán et al., 2000).

This study was performed in the Cherfech irrigation district, located in northern Tunisia. The irrigated area is 2,022 ha, and has been in operation since the 1960s. The project distributes water from the main reservoir through the Medjerda Canal. The system was originally designed for surface irrigation, mainly micro basins and short blocked-end borders, due to limitations in levelling quality. The soils in the area are rich in retractile clay, and have low organic matter content (Gharbi, 1975). As a result, large cracks appear following an irrigation event.

Zairi et al. (2003) diagnosed irrigation performance in the district, and reported that efficiency exceeded 60% in only a few fields, with most losses due to deep percolation. The main causes of irrigation inefficiency were poor land levelling and low irrigation discharge. Correcting land levelling would require moderate investments, while increasing the irrigation discharge could be just as expensive as installing a pressurised irrigation system (Playán et al., 2000). In the local conditions, it is important to explore management improvement techniques that result in better use of the current on-farm discharge.

This study aims to evaluate alternate furrow irrigation, as a feasible management improvement technique in which only half of the furrows in a field (every other furrow) are irrigated in a given event. The first reference to alternate furrow irrigation dates from 1968, when Grimes et al. (1968) presented the application to cotton in the San Joaquín Valley of Califorma. A decade later, Reeves and Stone (1977) applied the system to grain sorghum in

Oklahoma. Crabtree et al. (1985) presented a complete report on alternate furrow irrigation for soybeans in Oklahoma, in which a three-year experiment was used to conclude that alternate furrow resulted in 15% yield reduction and 40-50% water conservation. According to those authors, these results constituted an acceptable trade-off for subhumid or semiarid regions. Similar results were reported for the same crop in Nebraska by Graterol et al. (1993). Kang et al. (2000a and 2000b) reported an experiment on maize, combining alternate furrow and deficit irrigation. These authors compared three different furrow treatments:

– Alternate furrow irrigation (AFI): one of the two neighbouring furrows was alternately irrigated during consecutive irrigation events.

– Fixed furrow irrigation (FFI): irrigation was fixed to one of the two neighbouring furrows.

– Conventional furrow irrigation (CFI): every furrow was irrigated during each irrigation event.

Their results favoured the AFI treatment, which outperformed FFI and CFI in terms of water use. Horst et al. (2005) analysed water conservation potential in Fergana Valley (Uzbekistan), and identified long alternate furrows as an optimum practice, leading to application efficiencies and distribution uniformities of about 80%. Sepaskhah and Parand (2006) reported that alternate furrow irrigation resulted in significant reduction in maize grain yield. Du et al (2010) recommended alternate furrow irrigation for wide-spaced cereals in Northern China.

The goal of this study was to explore alternate furrow irrigation as a management improvement technique in the Cherfech irrigation district of Tunisia. The rationale is that inefficient furrow irrigation can be upgraded by irrigating alternate furrows if the crop can still obtain enough water to sustain its productive capacity at a reasonable level. The local cracking soils that currently result in low irrigation performance can facilitate horizontal water redistribution in an alternate furrow scheme. The study addressed the effect of alternate furrow irrigation on soil infiltration, irrigation performance, crop yield and water productivity in a potato crop.

Materials and Methods

Experimental site

Field trials were carried out at the INRGREF Experimental Station located in Cherfech, low Medjerda valley, 20 km north of Tunis (37º N, 10,5° E, elevation of 328 m). The Experimental Station is located in a semi-arid environment. The local meteorological records extend from 1980 to 2008 (Table 1). The average precipitation is 443 mm yr^{-1}. The seasonal distribution of rainfall presents the typical Mediterranean pattern, with minima in summer, the period of maximum crop water requirements. The average reference evapotranspiration (ET_0), estimated by the Penman-Monteith method (Allen et al., 1998) is 1,112 mm yr^{-1}.

The soil texture at the experimental station can be classified as clay silt, according to the International Soil Science Society classification (28% clay, 49% silt, 23% sand). Soil depth exceeds 1.20 m. The soil water depth at field capacity and wilting point were 420 mm m^{-1} and 260 mm m^{-1}, respectively, as determined using pressure plates. The total available water (TAW) (Walker and Skogerboe, 1987) was determined as 160 mm m^{-1}.

The irrigation system, connected to the Medjerda canal, consists on a tertiary ditch and a plastic gated pipe. The soil longitudinal slope of the experimental field was 0.2 %, and there was no cross-sectional slope. The experimental farm is equipped with irrigation canals, low-pressure pipelines, volumetric flow meters and gated pipes for furrow irrigation.

The experimental setup

Experiments were conducted on a blocked-end furrow irrigated field. The furrow spacing was 0.75 m. The field was divided into three adjacent irrigation treatments with a furrow length of 100 m each. This furrow length can be considered representative of the local conditions. Each treatment consisted of 20 furrows, resulting in a width of 15 m. All furrows were identical, with a bottom width of 0.10 m and a side slope of 1.6 (horizontal to vertical). A statistical design oriented towards the use of ANOVA techniques would have been desirable to adequately assess the response of yield and other crop variables to the experimental treatments. Farré and Faci (2009) presented an ANOVA-oriented field experiment for maize irrigated with micro level-basins. The area of their experimental plot was 45 m^2, while in this case the area of the experimental plot was 1,500 m^2. The large area of the experimental plot prevented the use of replications.

The irrigation treatments are described in this paper following the terminology proposed by Kang et al. (2000a and 2000b). Two of the treatments involved alternate furrow irrigation: AFI and FFI. Finally, a third treatment used CFI. The CFI treatment was irrigated with the goal of satisfying crop water requirements. For this, an irrigation schedule was prepared using the local average crop evapotranspiration records and the seasonal precipitation records. The maximum rooting depth was 0.6 m, corresponding to field observations. The soil water depletion coefficient p was 0.48 at the initial crop development phase, 0.35 at the mid season phase and 0.46 at the end of the late season phase (Doorenbos and Kassam, 1979). Consequently, irrigation was applied when crop water requirements exceeded 34 - 46 mm, depending on the crop phase. Irrigation in AFI and FFI followed the schedule of the CFI treatment, but irrigated only half of the furrows.

Irrigation was cut off when advance reached 95 m on the average of all furrows. This is in compliance with local farmers' practice in the area. Slatni et al. (2000) analysed the effect of furrow discharge on advance and infiltration in the local conditions. Following their results, furrow discharges of 2 l s^{-1} and 1 l s^{-1} were targeted for the first and subsequent irrigations, respectively.

The experimental crop

A potato crop (*Solanum tuberosum*, cv. Arinda) was planted on February 14, 2008. Planting was performed on the furrow crests, with a density of 45,000 tubers ha^{-1} and a tuber spacing of 0.75 m x 0.30 m. Harvest was performed in June 24, 2008. Crop yield was determined from sampling areas with an area of 1 m^2. All tubers in each sampling area were harvested and weighed. A total of 10 sampling areas were randomly distributed in each treatment. Since the experiment did not follow a statistical design, the yield of the different treatments cannot be regarded as a firm conclusion of this experiment.

The determination of crop water requirements followed Allen et al. (1998). The initial, development, mid season and late season phases lasted for 35, 30, 50, and 17 days, respectively, for a complete crop cycle of 132 days. The crop coefficients (*Kc*) used for this experiment were 0.73 for the initial phase, 1.12 for the mid season, and 0.40 for the late season. Daily values of *Kc* were obtained using the KcISA software (Rodrigues and Pereira, 1999). Local meteorological data were used to determine the crop water requirements of the experimental season.

An initial irrigation was performed with portable sprinkler equipment operating at high uniformity. This irrigation was applied at 1 DAP, and amounted to 25 mm in each treatment. All three treatments were irrigated at the same time. The first furrow irrigation was applied at 37 DAP, while the seventh and last furrow irrigation was applied at 106 DAP (Table 2).

Irrigation evaluation and simulation

Evaluations were performed for the seven furrow irrigation events (Table 2). In all irrigations, evaluations included discharge and time of cut-off measurements. In irrigations 1, 2 and 3, the advance curve was additionally determined from observations at 10 m intervals along two furrows per treatment. The recession curve was not determined since it was not possible to access all treatments after completion of advance. Recession occurred at about the same time along the furrows, with local soil depressions accumulating water for a few extra minutes. The average duration of the recession phase in irrigations 1, 2 and 3 was estimated as 40 min.

Soil water was gravimetrically determined before and after irrigation events 1, 2 and 3. Two furrows were sampled per irrigation treatment. These were the same furrows used for the determination of irrigation advance. Five soil water profiles (distributed along the furrow crest at distances from the inlet of 5, 25, 50, 75 and 95 m) were measured at 0.10 m depth intervals to a total depth of 1.00 m. Successive auger holes were offset by about 0.3 m along the furrow to avoid interference from the previous samplings. Soil water at field capacity could be estimated as the maximum soil water after irrigation at the CFI treatment (417 mm m^{-1}). This estimate is coincident with the measurement obtained using pressure plates (420 mm m^{-1}). Soil water measurements were also used to determine the target irrigation depth (Zr, mm) as the difference between field capacity and the average soil water content prior to each irrigation event. Soil water storage following irrigation events 1 to 3 was determined as the difference in soil water after and before irrigation.

Three performance parameters were used in this study to characterise individual irrigation events:

- Application Efficiency (Ea, %), determined as the ratio of the average depth of irrigation water contributing to Zr to the average depth of irrigation water, multiplied, times 100 (Burt et al., 1997).

- Low-quarter Distribution Uniformity (DU_{lq}), determined as the average low-quarter depth divided by the average infiltrated depth (Burt et al., 1997).

– Storage Efficiency (*Es*, %), determined as the percentage of soil water deficit refilled by irrigation (ratio of average infiltration minus average deep percolation to target irrigation depth, times 100).

In the present experiment, determination of *Ea*, DU_{lq} and *Es* required analysis of irrigation advance, discharge, irrigation time, and soil water. Determinations were therefore restricted to irrigation events 1-3.

Direct furrow infiltration measurement meets significant challenges in the Medjerda valley, due to soil cracking and to the resulting lateral infiltration. As a consequence, obtaining the parameters of an empirical infiltration equation from the advance curve is a prominent alternative. The WinSRFR model, version 3.1 (USDA, 2009) was used for this purpose. Roughness was characterised by a Manning *n* of 0.02, estimated using flow depth measurements at the upstream side of the furrows (data not presented). The most common empirical infiltration equation is the two-parameter Kostiakov equation (Walker and Skogerboe, 1987):

$$Z = k\tau^{a} \qquad [1]$$

where Z is the infiltrated depth (mm), τ is the opportunity time (h), and k (mm h^{-a}) and a (dimensionless) are the empirical Kostiakov parameters. The WinSRFR model uses a four-parameter, modified Kostiakov equation:

$$Z = k\tau^{a} + b\tau + c \qquad [2]$$

where b (mm h^{-1}) is the basic, long-term infiltration rate, and c (mm) is the instantaneous infiltration (Z at $\tau = 0$), characteristic of cracking soils. Furrow infiltration is a two-dimensional process which can be simulated as a one-dimensional process using equations [1] or [2]. The WinSRFR model expects infiltration to be specified as volume per unit length and per unit width. We used the furrow spacing (1.50 m in AFI and FFI, 0.75 m in CFI) as the infiltration width in order to determine Z (mm).

The first experimental approach to infiltration estimation consisted on the use of three double-ring infiltrometers in the study plot. Measurements were taken for about 700 min. The infiltrometers were only used to assess the importance of the basic infiltration rate in the local conditions. Statistical regressions were developed for all rings following Eq. [2]. The b parameter was negative for all three rings, in a clear contradiction of its physical meaning. Parameter b was neglected for the experimental conditions, and infiltration estimation from advance focused on two alternatives: 1) estimating k and a in Eq. [1]; and 2) estimating k and c in a Phillip-based version of Eq. [2] (Clemmens and Bautista, 2009) in which a = ½ and b = 0.

The estimation of infiltration and roughness parameters has been performed in the literature using different approaches and input data. Elliott and Walker (1982) presented the two-point method for the estimation of infiltration from advance time to 50 % and 100 % of the furrow length. A number of numerical procedures for the estimation of infiltration parameters have been reported in the literature (Bautista and Wallender, 1993; Walker, 2005; Strelkoff et al; 2009). In this paper, a trial and error procedure was used to estimate pairs of infiltration parameters (k - a and k - c) resulting in best fit between WinSRFR simulations and the observed advance curves (Playán et al., 2000). For each irrigation event, and for each value of a or c, the value of k was identified that resulted in the best visual fit to the observed advance curve. Values of a were explored using ±0.05 increments. Values of c were explored using 5 mm increments. Parameter estimation would have been more accurate if the recession curves had also been available.

Simulated infiltration was compared to experimental observations of soil water storage following irrigations 1 to 3 (five points along the furrow). The Root Mean Square Error in soil water storage (*RMSEs*) was determined for each treatment and irrigation event. The average value for each infiltration estimation procedure was used to establish the method that was better adapted to the experimental conditions. The observed and simulated recession time was also used for this purpose. Finally, the abovementioned irrigation performance parameters were obtained from simulation results.

Crop water-yield simulation

The ISAREG model (Teixeira and Pereira, 1992) was used to perform a water balance for the three treatments and to model yield response to water stress. ISAREG is a soil-crop-water simulation model. The soil is managed as a single reservoir, refilled by irrigation and precipitation and depleted by drainage and crop evapotranspiration. Evapotranspiration proceeds at maximum rate until the soil water depletion (determined as the ratio of current to maximum depletion) exceeds the critical value (p). Reductions in crop evapotranspiration are introduced into the model if soil water depletion exceeds p. The abovementioned p values were used in all simulations. Yield response to water stress is estimated in ISAREG using the yield response coefficient (Ky) presented by Doorenbos and Kassam (1979). Following these authors, a value of 1.1 was adopted for this parameter. The calibration and validation of the ISAREG model for the conditions of Tunisia has been described by Teixeira et al. (1995) and Zairi et al. (1998).

The gross irrigation depths observed in each irrigation evaluation for each treatment were used in the simulations. The model provided estimates of actual crop evapotranspiration and standardised crop yield reduction. Consideration of unstressed crop yield in the experimental conditions permitted water stressed crop yield to be estimated.

Deficit irrigation was simulated by reducing the number of irrigations. To reduce the number of irrigations by one, the last irrigation was eliminated and the second to last was applied on the day of the last irrigation (106 DAP). The interval between the remaining irrigations was rescaled proportionally. Simulations were performed with 6 and 5 irrigation events, in an attempt to characterise the effect of restrictive alternate/conventional furrow irrigation schedules on crop evapotranspiration, yield and water productivity.

The different irrigation treatments and deficit irrigation scenarios were analysed using hydrological, crop yield, irrigation efficiency and water productivity parameters. Burt et al. (1997) presented a definition of irrigation efficiency (IE):

$$IE = \frac{\text{Volume of irrigation water beneficially used}}{\text{Volume of irrigation water applied - }\Delta\text{ storage of irrigation water}} 100 \qquad [3]$$

We assumed that all precipitation water recorded during the irrigation season was beneficial, and that soil water storage was the same at the beginning and end of the irrigation season. Consequently, irrigation performance was estimated as the percentage of simulated crop ET minus precipitation to gross irrigation water. Following Playán and Mateos (1996), two water productivity indexes (WP_2 and WP_4, kg m^{-3}) were computed. WP_2 designates the ratio of yield to irrigation water diversion (gross irrigation depth), whereas WP_4 refers to the ratio of yield to irrigation water beneficially used (actual crop evapotranspiration, in this case).

Results and discussion

Crop water requirements

Figure 1 presents the precipitation (*P*) and crop evapotranspiration (ET_c) during the experimental season. Crop water requirements amounted to 2-4 mm d^{-1} before tuber formation, and 4-6 mm d^{-1} during tuber formation. Maximum crop water requirements were observed at 103 DAP, with 7.7 mm d^{-1}. After this day, a decrease could be observed, leading to ET_c values of about 2 mm d^{-1} at the end of the cycle. The seasonal ET_0 and precipitation amounted to 465 and 120 mm, respectively, while the seasonal ET_c was 444 mm.

Irrigation evaluations

Seven surface irrigations were applied to the crop between DAP 37 and 106 (March 22 and May 30) (Table 2). The first surface irrigation event resulted in large irrigation depths, even though a higher discharge was used than in the rest of irrigations. The average difference between the first irrigation and the rest amounted to 10, 11 and 23 mm for treatments AFI, FFI and CFI, respectively. The application depths for irrigations 2 – 7 showed small variations, with coefficients of variation of 5, 11 and 8 % for treatments AFI, FFI and CFI, respectively. Seasonal surface irrigation amounted to 458, 419 and 634 mm for the AFI, FFI and CFI treatments, respectively. AFI resulted in slightly more water application than FFI (9 %), while CFI applied 45 % more water than the average of the two alternate furrow treatments.

The evolution along the furrow of soil water storage during irrigations 1 to 3 for each irrigation treatment is presented in Figure 2. The figure also presents the average storage pattern for each treatment, which usually shows maximum values at the upstream part of the furrows. This is the expected trend for blocked-end furrow irrigation when irrigation is cut off before completion of advance.

Figure 3 presents the advance curves corresponding to irrigations 1 to 3 in the three treatments. Advance curves were used to fit two sets of infiltration parameters (Table 3). Comparison with observed soil water storage values resulted in average *RMSEs* of 25 and 26 mm for sets of parameters *k-a* and *k-c*, respectively. An important factor contributing to *RMSEs* is that observed recharge was on the average 18 mm lower than simulated storage. Evapotranspiration and drainage water losses between the experimental storage measurements before and after the irrigation event can explain these differences. The average simulated duration of the recession phase (all treatments, all irrigation events) were 20 and 14 min for the *k-a* and *k-c* infiltration parameter sets, respectively. The simulated duration of the recession phase was in both cases lower than observed (40 min). Observed recession may have been overestimated due to the low quality of levelling, which resulted in undulations accumulating recession water. This analysis permitted the conclusion that both sets of infiltration parameters adequately reproduced the experimental irrigations, with the *k-a* set, corresponding to the Kostiakov infiltration equation, producing slightly better results.

The WinSRFR simulations (Fig 3) using optimum *k-a* infiltration parameters in each case usually resulted in very good agreement along the advance curve. CFI irrigations 1 and 2 presented the poorest agreement between observed and simulated advance. In these irrigation events, increasing infiltration would lead to incomplete advance. In each irrigation event, the minimum time of advance was observed for treatment CFI. Differences between the times of advance of treatments AFI and FFI were in general not important. Figure 4 presents a plot of opportunity time (min) *vs. k-a* infiltration (mm) for the nine cases. The plot is intended to facilitate discussion of the infiltration curves. In all three cases infiltration decreased from the first to the third irrigation of the season. The CFI treatment showed the highest infiltration per unit area, and differences were not clear between AFI and FFI. Alternate furrow irrigation succeeded in reducing infiltration in the experimental conditions, thus potentially contributing to water conservation. These results are in agreement with previous observations by Kang et al. (2000a and 2000b).

The target irrigation depth (Z_r, determined from soil water) ranged between 60 and 84 mm between treatments and irrigation events. No trend could be observed in these values, which are subjected to strong spatial variability (Table 4). Irrigation performance parameters are presented in Table 4 for the two sets of infiltration parameters. Agreement between performance parameters was in general very good, with the exception of three estimates of DU, which differed by more than 0.05.

The following discussion on performance indexes is restricted to the *k-a* infiltration model. Application efficiency ranged between 70 % and 100%, indicating that in general deep percolation losses were moderate. The highest average *Ea* corresponded to FFI, with 100 %, followed by AFI with 88 %, and finally CFI with 72 %. Regarding DU_{lq}, AFI obtained the highest average score (0.84), followed by CFI (0.77), and finally by FFI (0.75). The AFI and CFI obtained an average *Es* of 98 %, while FFI only obtained 81 %. The high *Ea* of the FFI treatment is due to partial replenishment of soil water deficit. In the three analysed irrigation events, treatments AFI and CFI adequately replaced soil water depletion, with AFI being more efficient than CFI.

Crop yield and water productivity

Crop yield showed similar patterns among treatments, with only limited variations along the furrows (Fig. 2). The average yield in each plot was 38.1 t ha^{-1} for AFI, 35.6 t ha^{-1} for FFI and 42.4 t ha^{-1} for CFI. As previously discussed, these results do not permit firm, statistically sound differences between treatments to be established. Nevertheless, they are useful to determine an average experimental yield of 38.7 t ha^{-1}.

Differences in yield between treatments were established using a crop water-yield simulation approach. Table 5 summarises the simulation results for the experimental case, characterised by seven surface irrigation events. ISAREG did not detect differences between the treatments in actual evapotranspiration (411 mm) or crop yield reduction (0 %). *IE* was much higher for the alternate furrow irrigation treatments (60 % for AFI and 66% for FFI) than for the CFI treatment (44%). While WP_2 was affected by the differences in gross irrigation water (ranging between 5.9 and 8.8 kg m^{-3}), WP_4 reached a constant value of 9.4 kg m^{-3}. The highest *IE* and WP_2 were obtained for the FFI treatment.

Simulations were extended to the two abovementioned scenarios corresponding to six and five irrigation events. ISAREG did not detect differences between treatments in any of these scenarios, although progressive reductions in actual ET_c and increases in yield reduction were observed. For each treatment *IE* and WP_2 attained maximal values in the five-irrigation treatments. However, WP_4 was maximal for the seven-irrigation scenario, indicating that full irrigation led to optimum income per unit of evapotranspiration. The irrigation treatments did not induce differences in WP_4 in the irrigation scenarios considered. The maximum IE value, 79%, was obtained for FFI using 5 irrigations. This irrigation efficiency is unusually high for furrow irrigation, although similar results have been reported for alternate furrow irrigation (Horst et al., 2005). Further research should be used to validate this figure obtained through simulation.

These simulated results suggest that, in the local conditions, alternate furrow irrigation in potato does not lead to decreased yield when compared to conventional furrow irrigation. These results contrast with those reported by Crabtree et al. (1985) and Sepaskhah and

Parand (2006). The small rooting depth and critical depletion that characterise the potato crop favour the performance of alternate furrow irrigation. The resulting target irrigation depth Z_r was relatively small. In these conditions, the large irrigation depths applied by CFI result in large deep percolation losses. In turn, the small irrigation depths applied by AFI and FFI do not result in significant soil water deficits. Additionally, the infiltration characteristics of the local soils could permit intense horizontal infiltration, thus providing appreciable water flow towards the non-irrigated furrows. The AFI and FFI irrigation treatments resulted in significant irrigation water conservation. Averaging the three scenarios, conservation amounted to 28 and 34 %, respectively, of the water used in CFI. This represents an important contribution to water conservation, particularly if future field experimentation confirms that crop yield is not affected by the introduction of alternate furrow irrigation. The similar performance reported under AFI and FFI is quite interesting, given that FFI is much simpler to implement than AFI. Since the change in irrigated furrow does not seem to be required, the implementation of alternate furrow irrigation seems to be feasible even when water distribution is based on earth ditches.

Zairi et al. (2003) identified low discharge and poor levelling as the main limiting factors of irrigation performance in the Cherfech irrigation district. Alternate furrow irrigation modifies soil infiltration, resulting in direct improvements in application efficiency. Additionally, the reduction in the number of irrigated furrows will permit increased furrow irrigation discharge, leading to additional performance improvements. Regarding land levelling, experimentation and simulation will have to be performed to assess the effect of alternate furrow irrigation on longer irrigation furrows. Furrow lengths exceeding 100 m could be obtained through improved land levelling. Prospects for water and labour conservation seem promising under these circumstances.

Conclusions

Infiltration equations were derived from data on irrigation advance for the three alternate furrow irrigation treatments and the first three surface irrigations of the season using the WinSRFR model. The results showed how, in the local cracking soils, infiltration was clearly higher for CFI than for AFI and FFI. Alternate furrow irrigation reduced furrow infiltration, thus enabling water conservation. The ISAREG model could not identify differences in yield between the three irrigation treatments for irrigation scenarios involving seven, six and five seasonal surface irrigation events. As a consequence, alternate furrow irrigation resulted in water conservation of 28 % for AFI and 34 % for FFI. The FFI treatment showed a small improvement over the AFI treatment. Since FFI is easier to implement in field conditions, this could be the alternate furrow irrigation of choice for the experimental area. Additional field research will be required to confirm these findings, particularly in relation to potential yield differences between the three treatments. Alternate furrow irrigation stands as a low-cost alternative to conventional furrow irrigation, leading to significant increases in irrigation efficiency and in the productivity of irrigation water (WP_2).

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Table 1. *Climatic characterization of the study area based on the records of the Cherfech meteorologic station. The selected data include average minimum temperature (T_{min}), average maximum temperature (T_{max}), precipitation (P) and reference evapotranspiration (ET0).*

Month	J	F	M	A	M	J	J	A	S	O	N	D	Year
T_{min} (°C)	6.1	5.9	7.0	8.5	12.1	16.1	17.7	19.0	17.3	13.9	9.8	6.9	11.7
T_{max} (°C)	15.7	16.4	18.4	21.3	26.1	30.4	33.5	33.8	30.6	26.3	20.7	17.0	24.2
P (mm)	70	56	37	34	24	7	3	10	38	47	54	63	443
ET_0 (mm)	31	41	69	94	133	155	177	159	111	72	41	29	1112

Table 2. *Results of the simplified irrigation evaluations performed in each irrigation event for all treatments.*

Irrig. #	DAP	Treatment	Discharge ($l\ s^{-1}$ $furrow^{-1}$)	Time of cut off (min)	Gross irrigation depth (mm)
1	37	AFI	1.9	97	74
		FFI	1.9	91	69
		CFI	1.8	75	110
2	58	AFI	1.0	170	67
		FFI	1.0	169	64
		CFI	0.9	127	90
3	69	AFI	1.0	166	63
		FFI	0.9	141	53
		CFI	0.9	118	88
4	79	AFI	1.0	167	67
		FFI	1.0	130	53
		CFI	1.0	110	88
5	88	AFI	1.0	150	60
		FFI	1.0	133	53
		CFI	1.0	119	96
6	96	AFI	1.0	152	60
		FFI	1.0	150	60
		CFI	1.0	110	88
7	106	AFI	1.0	165	67
		FFI	1.0	168	67
		CFI	1.0	92	74

Table 3. *Parameters of the two empirical infiltration equations estimated by simulation of irrigations 1, 2 and 3, all treatments.*

Irrig. #	Treatment	$Z = k\tau^{a}$		$Z = k\tau^{\frac{1}{2}} + c$	
		k (mm h^{-a})	a (-)	k (mm $h^{-½}$)	c (mm)
1	AFI	73	0.3	54	20
	FFI	73	0.3	52	20
	CFI	115	0.3	84	35
2	AFI	57	0.3	36	20
	FFI	55	0.3	34	20
	CFI	83	0.4	63	20
3	AFI	54	0.3	40	15
	FFI	45	0.4	29	20
	CFI	78	0.4	60	18

Table 4. *Target irrigation depth (Zr, mm) and irrigation performance indicators obtained by simulation using the two empirical equations for irrigations 1, 2 and 3, all treatments. Indicators include application efficiency, (Ea), distribution Uniformity (DU_{lq}) and Water Storage Efficiency (Es).Differences in DU exceeding 0.05 are marked in bold type.*

Irrig. #	Treatment	*Zr* (mm)	$Z = k\tau^{a}$			$Z = k\tau^{\frac{1}{2}} + c$		
			Ea (%)	DU_{lq} (-)	*Es* (%)	*Ea* (%)	DU_{lq} (-)	*Es* (%)
1	AFI	64	86	**0.82**	98	84	**0.73**	97
	FFI	83	100	0.72	83	100	0.70	83
	CFI	84	78	**0.95**	100	76	**0.74**	99
2	AFI	60	87	0.79	97	86	0.74	97
	FFI	76	100	0.78	84	100	0.75	84
	CFI	64	68	0.65	97	68	0.69	98
3	AFI	60	90	**0.90**	98	85	**0.69**	93
	FFI	70	100	0.75	77	100	0.74	77
	CFI	61	70	0.70	98	71	0.73	98

Table 5. *Experimental and simulated values of irrigation water, irrigation water conservation, crop ET, yield decrease, crop yield, irrigation efficiency and water productivity for the AFI, FFI and CFI treatments. Results are presented for the experimental conditions (7 surface irrigation events), plus two simulation scenarios based on 6 and 5 surface irrigation events.*

Variable	7 irrigations			6 irrigations			5 irrigations		
	AFI	FFI	CFI	AFI	FFI	CFI	AFI	FFI	CFI
Gross irrigation water (m^3 ha^{-1})	4,830	4,440	6,590	4,160	3,770	5,850	3,560	3,240	4,890
Water conservation respect to CFI (%)	27	33	-	29	36	-	27	34	-
Simulated actual crop ET (m^3 ha^{-1})	4,110	4,110	4,110	3,890	3,890	3,890	3,770	3,770	3,770
Simulated yield decrease (%)	0.0	0.0	0.0	19.8	19.8	19.8	23.0	23.0	23.0
Simulated crop yield (Mg ha^{-1})	38.7	38.7	38.7	31.0	31.0	31.0	29.8	29.8	29.8
IE (%)	60	66	44	65	71	46	72	79	53
WP_2 (kg m^{-3})	8.0	8.7	5.9	7.5	8.2	5.3	8.4	9.2	6.1
WP_4 (kg m^{-3})	9.4	9.4	9.4	8.0	8.0	8.0	7.9	7.9	7.9

Figure 1. *Daily reference evapotranspiration, crop evapotranspiration and precipitation during the experimental season.*

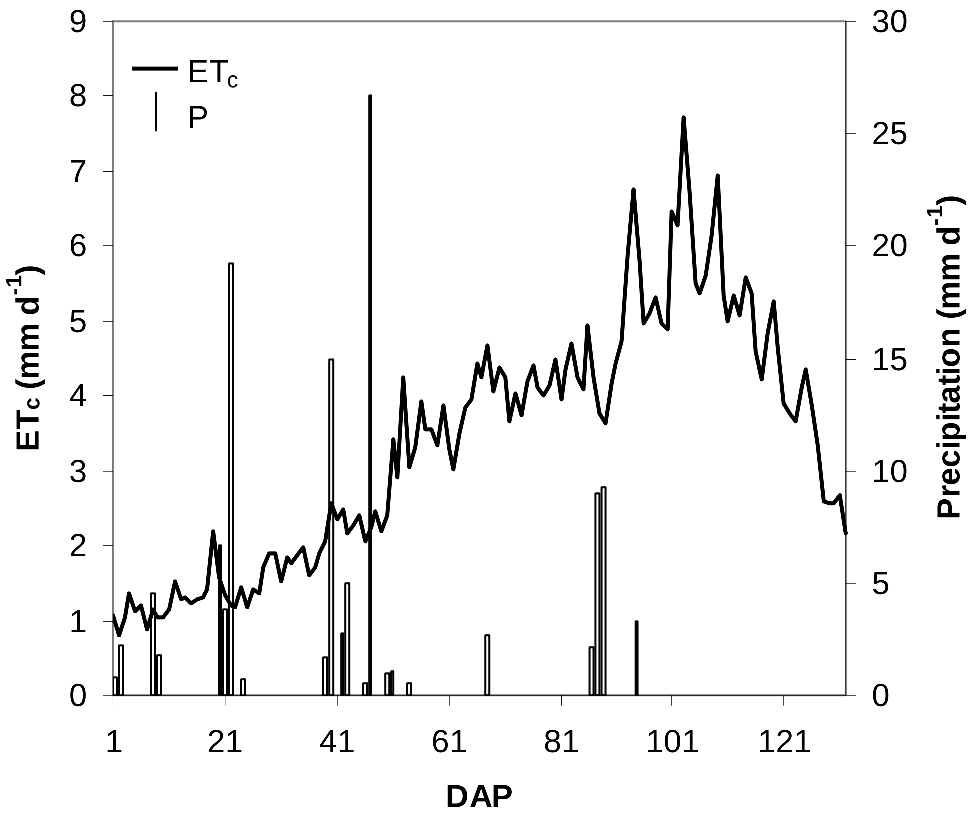

Figure 2. *Irrigation water storage (irrigations 1, 2 and 3) and potato yield along the furrow for all treatments. Symbols are as follows: the solid line indicates yield; the dashed line indicates average storage in irrigations 1, 2 and 3; and ●, ▲ and □ indicate storage in irrigations 1, 2 and 3, respectively.*

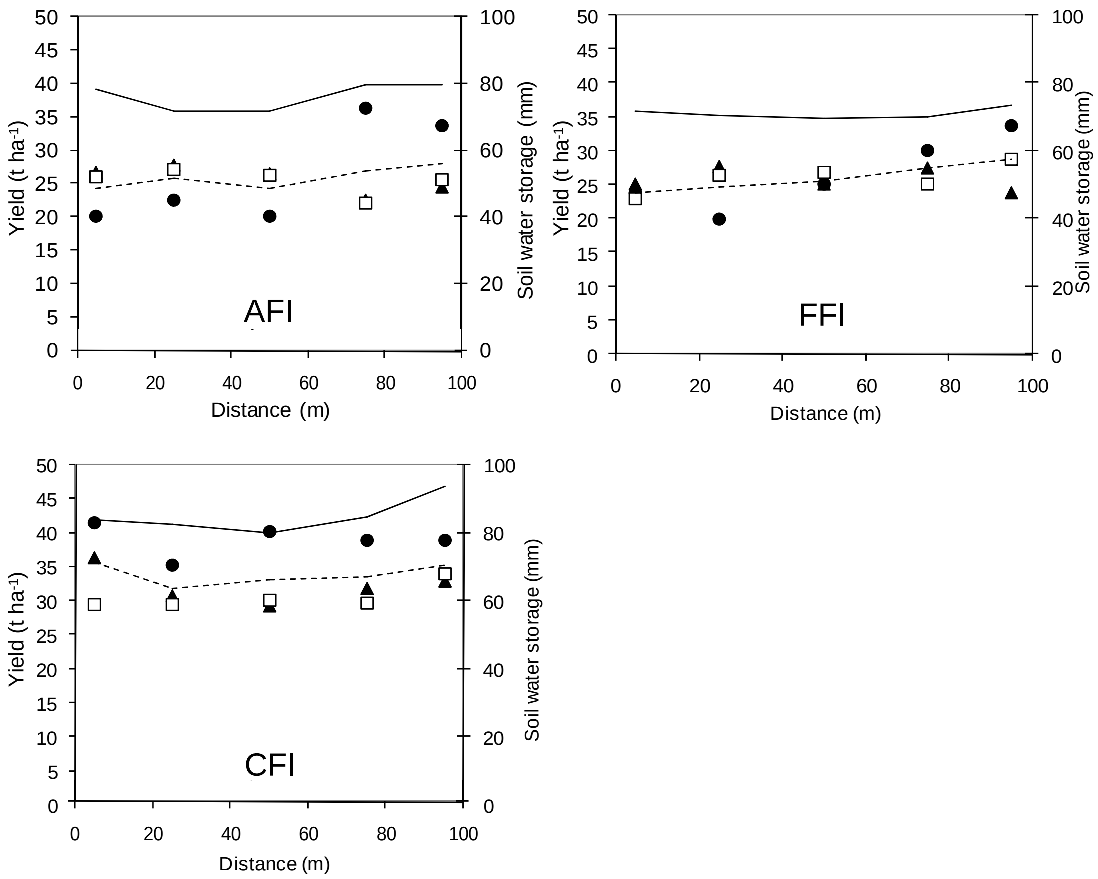

Figure 3. *Advance curves as observed (dots) and simulated with optimum Kostiakov infiltration parameters* ($Z = k\tau^a$) *(lines) in irrigations 1, 2 and 3, all treatments.*

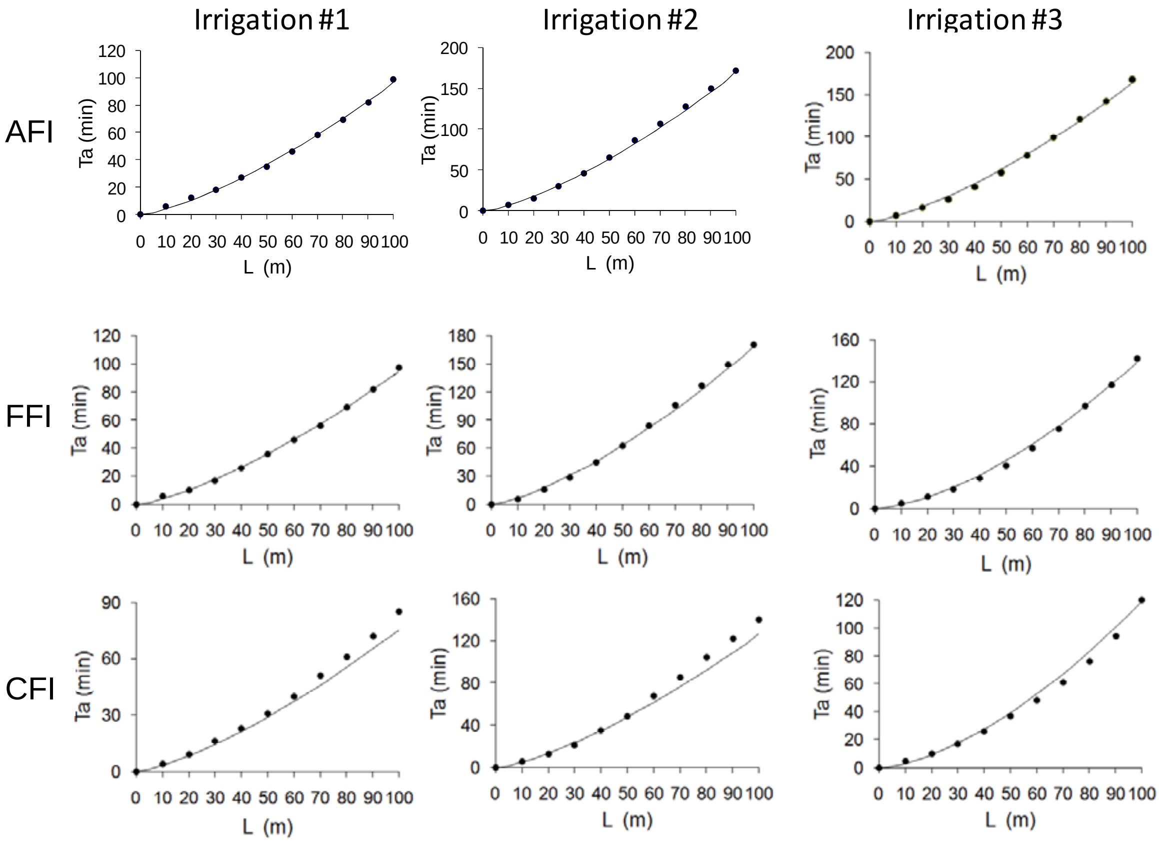

Figure 4. *Kostiakov infiltration curves ($Z = k\tau^a$) up to an opportunity time of 150 min corresponding to the combinations of all treatments and irrigations 1, 2 and 3.*